

SAGE III: A VISIBLE WAVELENGTH LIMB SOUNDER

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ABSTRACT

This paper will present a brief description of the SAGE III (Stratospheric Aerosol and Gas Experiment III) instrument that has been selected to fly onboard the National Polar Platform I (NPOP I) for the Earth Observational System (Eos) in 1996. The SAGE III instrument will perform earth limb sounding with the solar occultation technique measuring the ultraviolet (UV), the visible, and the near infrared (IR) wavelength solar radiation. The instrument will produce atmospheric data for the vertical distribution of aerosol, ozone, nitrogen dioxide, water vapor, and oxygen. The details of the instrument design, data flow, and processing requirements will be discussed here.

INTRODUCTION

The SAGE III instrument is part of a long heritage of space flight instruments that performed solar occultation measurements for remotely sensing the earth's atmosphere. The simple SAM (Stratospheric Aerosol Measurement) instrument was flown onboard the Apollo capsule during the Appollo-Soyuz Test project in 1975 (Pepin et al., 1977). SAM II was launched onboard the Nimbus 7 platform in 1978 (McCormick et al., 1979) and has operated continuously ever since. SAGE I was launched on the AEM II spacecraft in 1979 and operated for almost three years until the spacecraft malfunctioned in 1981 (McCormick et al., 1979). SAGE II was launched in 1984 on the Earth Radiation Budget Satellite (ERBS) platform (Maudlin et al., 1985) and is still operating flawlessly. SAGE III is currently being proposed for the NPOP 1 and the space station attach payload missions during the Eos mission in 1996. The instrument design has evolved from the simple one-channel SAM instrument with a hand-held pointing system to the sophisticated seven-spectral-channels sun photometer with spectral grating optics, automatic sun acquisition electronics, and mechanical scanning capability of the SAGE II instrument. The SAGE III instrument will expand on the experience and technology advances gained from previous SAGE missions to perform earth limb sounding with the solar occultation approach.

MISSION OBJECTIVES

The scientific objectives of the SAGE III experiment are to produce geophysical data on the vertical distribution of the key species in the upper atmosphere such as ozone, aerosol, water vapor, nitrogen dioxide, and oxygen; and to provide a long-term data base on these species for trends monitoring. The remote sensing approach is solar occultation. The major advantage of solar occultation measurements is that the instrument can be made to be almost totally self-calibrating. Both the radiance throughput and the spectral radiance response of the instrument can be calibrated against the solar radiation immediately during each measurement event, be it a spacecraft sunrise or sunset measurement. The fundamental measurements from the SAGE III instrument will be the ratio of solar radiance. The ratio of solar radiance is attenuated by the earth's limb to the unattenuated solar radiance values. Therefore, only relative radiance measurements are required and the requirement for absolute radiance measurement is totally relaxed. The spectral locations of the nine channels of the SAGE III instrument are illustrated in figure 1 together with the relative contribution of extinction by the various atmospheric species at a height of 18 km. Of the nine channels of SAGE III located at 310, 385, 450, 525, 600, 760, 940, 1020, and 1550 nm, the channels at 310 and 600 nm are for ozone measurement extending the altitude range from 5 km up to 90 km height. The channel at 450 nm is for nitrogen dioxide measurements; the channel at 940 nm is for water vapor measurement; the channel at 760 nm centering at the oxygen A band is for oxygen measurement; and the rest of the seven channels are for aerosol remote sensing.

INSTRUMENT DESCRIPTION

The SAGE III instrument as currently envisioned will be similar in design as the other SAGE instruments. Figure 2 shows the schematic of the sensor part of the instrument consisting of the scan head, telescope, and the spectrometer and detector subsystem. The scan head is made up of an elevation scan mirror that can scan both in elevation and azimuth, together with a sun tracker sensor for pointing and solar tracking. Incoming solar radiation is reflected by the scan mirror into the F/2 telescope to form the scanned image of the solar disc on the focal plane. A circular aperture limiting the view angle to a circular cone of one arc minute full angle at the focal will define the instrument's field of view. The same aperture also serves as the entrance slit to the spectrometer and detector subsystem. The spectrometer and detector subsystem consists of a stigmatic imaging concave reflection grating which can form a flat field image of the earth's limb spectrum on the 512-element silicon CCD detector array. The CCD detector array, in combination with an order-sorting segmented interference filter, measures the disperse radiation in three separated orders. As illustrated in figure 3, the CCD detector array measures first-order diffracted light from 280 to 800 nm, and from 910 to 1070 nm; second-order diffracted light from 410 to 455 nm; and third-order diffracted light from 356 to 400 nm. The IR channel centered at 1550 nm is situated at the grating zero order diffraction with a separate interference filter and discrete InGaAs detector. Each CCD pixel in the first order can produce 2-nm spectral resolution. In the second order, it can produce 1-nm spectral resolution. The broadband channel output of such channels as 1, 2, 4, 5, and 8, is obtained by electronically summing the appropriate adjacent pixel output for the desired spectral bandwidths. The fine spectral resolution channel output for NO₂, H₂O, and O₂ at 450 nm, 940 nm, and 760 nm, respectively, are obtained from electronically addressing the 20 individual pixels in each of these spectral bands.

SAGE III DATA ACQUISITION AND PROCESSING

The data acquisition operation for the SAGE III instrument will be similar to the previous SAGE instruments described by Chu and McCormick (1979). During a spacecraft sunset event, the instrument will slew in azimuth to acquire the sun. As soon as the sun sensor indicates that the sun is in the instrument's field of view, the scan mirror will scan in elevation until a full sun scan is obtained. During this time, several full-up scans will be obtained for the unattenuated solar limb profiles, while the solar Fraunhofer line positions will be monitored for subsequent wavelength calibration. The scan mirror will continue the elevation scanning across the solar disk until the sun is set beyond the horizon. Then the instrument will automatically shut off. For a sunrise event, the reverse procedure will be followed.

The irradiance measurements performed by the SAGE III instrument can be converted to the slant path transmission profile for each of the wavelength channels (pixel) by ratioing the solar scans transversing the atmosphere to the extraterrestrial solar scans. The procedure will be similar to the algorithms developed for the SAGE I and SAGE II missions as described by Chu and McCormick (1979). The transmittance function of the ray tangent height h_t , according to the Bouguer law, is given by

$$\begin{aligned} T_\lambda(h_t) &= \exp[-\delta_\lambda(h_t)] \\ &= \exp\left[-\int \sigma_\lambda(h) d\rho_\lambda(h)\right] \end{aligned} \quad (1)$$

where $\delta_\lambda(h_t)$ is the total slant path optical depth at wavelength λ with ray tangent height h_t ; σ_λ is the total extinction coefficient of the atmosphere as a function of altitude h and wavelength λ ; and ρ is the geometric path length corrected for refraction. Denoting the slant path optical depths as the measurements, equation (1) becomes a Fredholm equation of the first kind relating the measurement $\delta_\lambda(h_t)$ to the integral with the unknown function $\sigma_\lambda(h)$ as the integrant. Using numerical quadrature with unity weights and assuming the atmosphere is spherical symmetry and homogeneous, the integral can be replaced with a numerical sum over the products of the total extinction coefficients in each layer with the corresponding geometric ray path length in the layer.

Dividing the atmosphere into m homogeneous layers, equation (1) becomes

$$\delta_{\lambda}(h_i) = \sum_{j=1}^m P_{ij} \sigma_{\lambda}(h_j) \quad (2)$$

The total extinction coefficient at each tangent altitude is a linear combination of the extinctions of each of the species as given by

$$\sigma_{\lambda} = \sigma^{Ray}(\lambda) + \sigma^{O_3}(\lambda) + \sigma^{NO_2}(\lambda) + \sigma^{aero}(\lambda) \quad (3)$$

where $\sigma^{Ray}(\lambda)$ is the extinction coefficient for Rayleigh scattering; and $\sigma^{O_3}(\lambda)$, $\sigma^{NO_2}(\lambda)$, and $\sigma^{aero}(\lambda)$ are the extinction coefficients for ozone, nitrogen dioxide, and aerosol at wavelength λ , respectively. For ozone and nitrogen dioxide, the extinction coefficients are determined by the product of the species number density and their absorption cross section at the given wavelength. The aerosol extinction coefficient is a function of aerosol size distribution, shape, and index of refraction. For homogeneous, spherical particles, one has

$$\sigma^{aero}(\lambda) = \int_0^{\infty} Q(n, r, \lambda) N(r) dr \quad (4)$$

where $N(r)$ is the size distribution function and $Q(n, r, \lambda)$ is the extinction cross section for a particle with refractive index n and radius r , as computed from Mie theory.

Equations (2) and (3) represent the SAGE III measurements as a function of wavelengths and heights, while the solution is in the form of a function of different species in vertical altitudes. The wavelength-dependent part of the measurement solely represents the overlapping contributions from the different species, and is independent of the height variable. The inversion process would generally require a two-step procedure to separately handle the wavelength and height variables. One part of the inversion process decouples the different wavelength measurements into individual species contribution, while the other part of the procedure deconvolutes the slant path optical depth profiles into vertical extinction profiles. Two different approaches to the solutions of equations (2) and (3) have been discussed by Chu et al., (1989) for the study of the SAGE II inversion algorithm.

Figure 4 illustrates the data flow block diagram for SAGE III data processing. SAGE III data will consist of raw count radiance data as a function of time for the nine spectral channels sampling at 64 times per second, plus the accompanying engineering data. The data processing software will be modeled after the SAGE II data processing algorithms (Chu, et al., 1989). The algorithms can be separated into three main sections: the driver section, followed by the transmission section, and finally the inversion section. The driver section handles data screening and merges necessary ancillary data such as the spacecraft's ephemeris data and the instrument's engineering data. The transmission section performs calibration and normalization of scan data by properly localizing each radiance measurement. This is accomplished only after the extraterrestrial solar scans for each channel have been selected and screened, and individual solar radiance measurements have been located both on the solar limb and in the atmosphere as slant path tangent height. The inversion section performs the inversion by converting the transmission data into geophysical parameters describing the vertical distributions of the various species; aerosol, ozone, nitrogen dioxide, water vapor, and oxygen molecules. A detailed description of the various sections of this algorithm have been discussed elsewhere (Chu and McCormick, 1979; Chu et al., 1989).

The overall inversion procedure of calibrating raw scan data into optical depth profiles and the subsequent inversion technique are complex. The complete SAGE III measurements require significant computer storage and computation power for processing at all the spectral channels available. However, simplified processing approaches can be implemented for selected wavelength regions where a single species dominates the measured signal. For example, aerosol signature will dominate the measurements at the 1550-nm and 1020-nm channels with negligible contribution from Rayleigh scattering. Similarly, at the 600-nm wavelength channel, the ozone contribution will dominate the measurements with small aerosol contribution below 20-km altitude. For the cases considered above, quick-look aerosol and ozone profiles can be obtained from less sophisticated

algorithms. These algorithms will use parameters interpolated from precalculated tables using standard atmospheric models. The tables could contain such information as sun shape changes caused by atmospheric refraction, Rayleigh extinction profiles, and other variables needed for quick-look data processing. The inversion procedure will be simpler because no separation of the different species contribution will be required. This kind of quick-look processing is ideally suited for the onboard processing unit being considered for the Eos system.

SUMMARY

A brief description of the SAGE III instrument and the anticipated data processing schemes have been presented here. The instrument design is still in the conceptual stage and is currently being finalized during the phase A-B activities of the Eos project. The anticipated data processing activities discussed here represent the cumulated experience acquired from processing the previous satellite missions such as SAM II, SAGE I, and SAGE II. It is anticipated that as the instrument design becomes mature, the data process scheme will necessarily be updated and modified.

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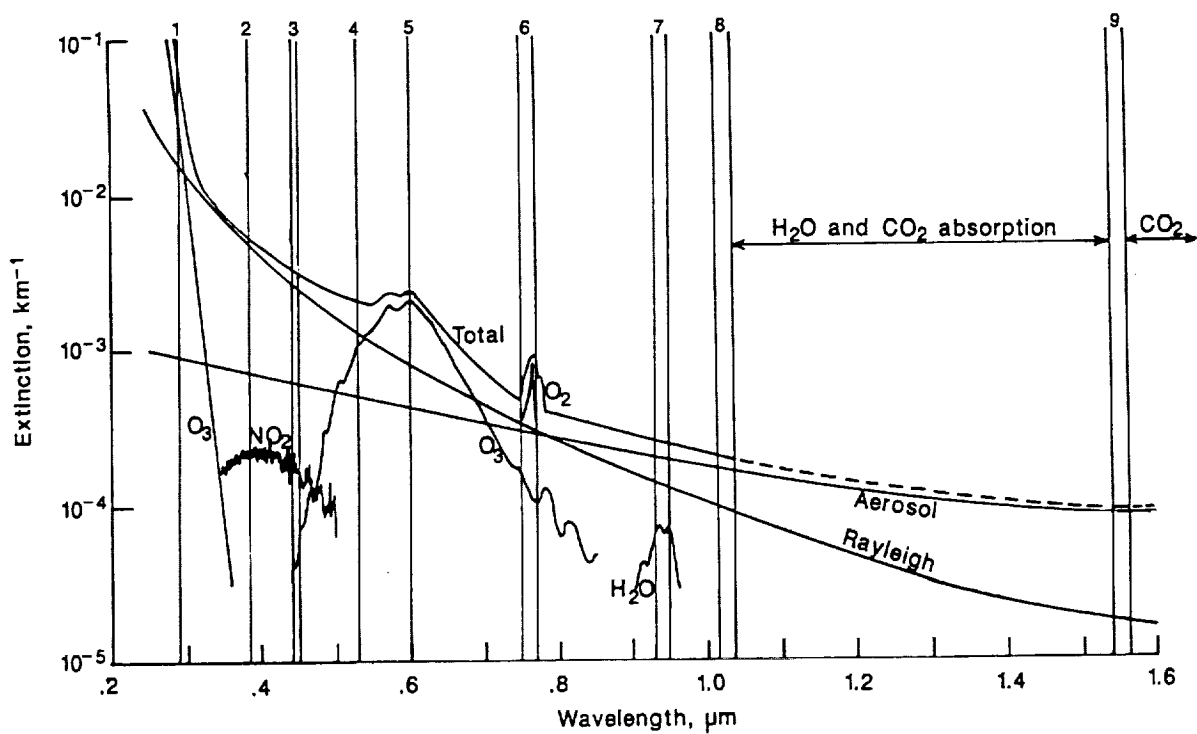


Figure 1. SAGE III channel locations.

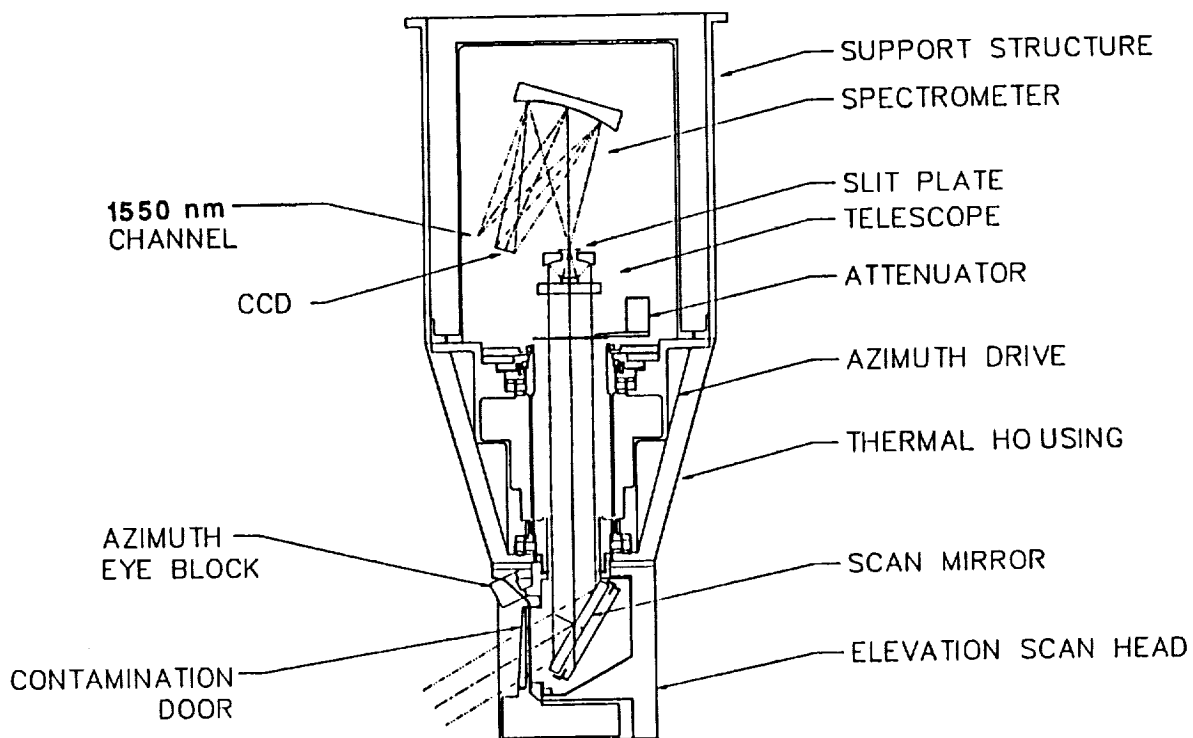


Figure 2. Schematic of SAGE III instrument.

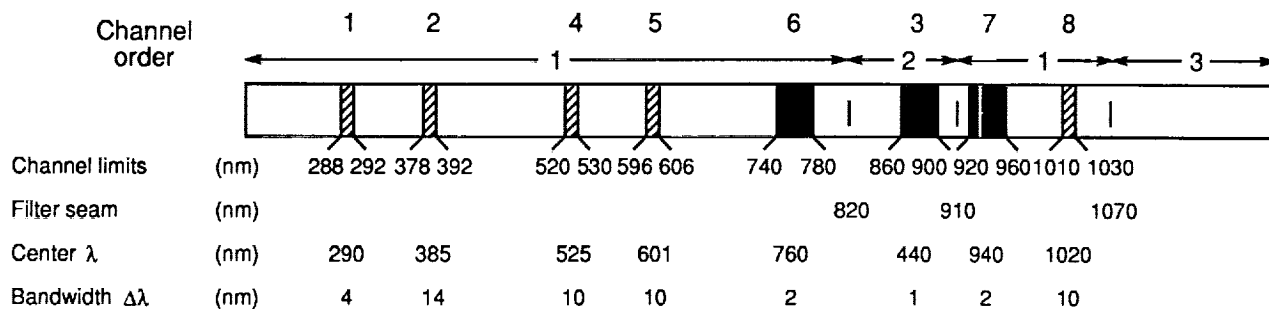


Figure 3. CCD detector array with spectrum.

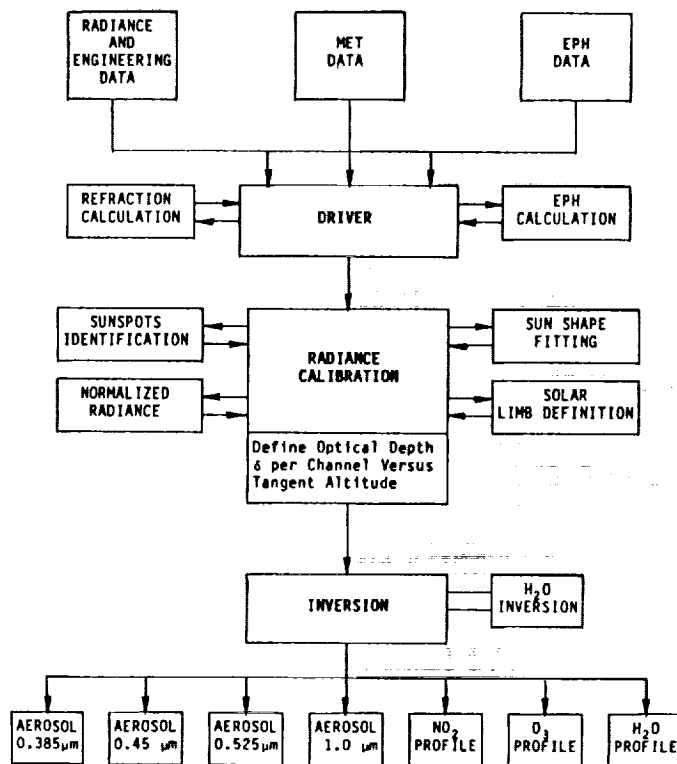


Figure 4. Data flow block diagram for SAGE III data processing.

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